

Noise Adding Radiometer Performance Analysis

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The DSN noise adding radiometer (NAR) measurement accuracy is analyzed. The NAR capability is part of the Precision Power Monitor function recently introduced in the DSN. The potential system noise temperature measurement accuracy is estimated to be about 1.5% (1σ) with the 1 kelvin noise diode. Performance verification requires comparison noise temperature measurements with the manual Y factor method and routine monitoring of critical elements in the NAR system such as system linearity and noise diode calibration. A technique is presented to calibrate and reduce the effects of the receiving system nonlinearity. Unsatisfactory performance or degradation of these critical NAR elements would require appropriate system upgrading.

I. Introduction

A noise adding radiometer (NAR) is being implemented (Fig. 1) in the DSN as an integral part of the Precision Power Monitor (PPM). The NAR is required to convert signal-to-noise ratio (SNR) measurements to signal power. In addition the NAR is available with stand-alone capability.

V_2 = detector output voltage, noise diode on, V

V_1 = detector output voltage, noise diode off, V

α = detector nonlinearity constant, V^{-1} (=0 in an ideal detector)

The NAR noise temperature measurement resolution is given by Ref. 1.

II. Theory

The fundamental equation for the NAR is (Refs. 1, 2):

$$T_{OP} = T_N / (Y - 1) \quad (1)$$

where

T_{OP} = system operating noise temperature, K (defined at system input reference plane)

T_N = noise diode injected noise temperature, K (defined at system input reference plane)

$Y = (V_2 + \alpha V_2^2) / (V_1 + \alpha V_1^2)$, ratio

where

τ = measurement time, s

B = predetection bandwidth, Hz

For example, if $T_{OP} = 20$ K, $\tau = 10$ s, $B = 10^7$ Hz, $T_N = 100$ K, then

$$\Delta T_{OP} \approx 0.005 \text{ K}$$

T_N can be calibrated by connecting the receiver input to the ambient termination. With T_{OP} known, the NAR is used to solve

$$T_N = T_{OP}|_{AMB} (Y - 1) \quad (3)$$

using (assuming a perfectly matched system with transmission line at temperature T_p)

$$T_{OP}|_{AMB} = T_p + T_E \quad (4)$$

where

$$T_E = \text{equivalent noise temperature of the receiver, K} \\ = T_M + T_F$$

$$T_M = \text{maser noise temperature, K}$$

$$T_F = \text{follow-up receiver noise temperature, K}$$

$$T_p = \text{physical temperature of ambient temperature, K}$$

In the above, T_p is measured, T_M^* is assumed known from laboratory measurements and T_F is determined from the maser on-off method.

$$T_F \approx T_p / Y_{00} \quad (5)$$

where

$$Y_{00} = \text{receiving system } Y \text{ factor with maser turned off and on, ratio}$$

The calibration resolution of T_N is given by (see Appendix A)

$$\Delta T_N = 2T_N(1 + T_{OP}/T_N)/\sqrt{\tau B} \quad (6)$$

For example, if $T_{OP} = 300$ K, $\tau = 10$ s, $B = 10^7$ Hz, $T_N = 100$ K, then

$$\Delta T_N = 0.08 \text{ K} = 0.08\%$$

However, if $T_N = 1$ K in this example, then

$$\Delta T_N \approx 0.06 \text{ K} = 6\%$$

which is unsuitable since a 6% error in T_N results in a 6% error in T_{OP} , Eq. (1), (i.e., a "low" noise diode cannot be calibrated directly using the ambient termination technique with "short" integration time). If T_N is small it is useful to use a larger T_N with a calibration transfer technique using both the ambient termination and the antenna. This calibration technique consists of:

- (1) Calibrating T_{NH} using the ambient termination with Eq. (4)

$$T_{NH} = T_{OP}|_{AMB} (Y - 1) \quad (7)$$

- (2) Calibrating the system operating noise temperature on the antenna

$$T_{OP}|_{ANT} = T_{NH}/(Y - 1) \quad (8)$$

- (3) Calibrating T_{NL} using the known T_{OP} from step 2

$$T_{NL} = T_{OP}|_{ANT} (Y - 1) \quad (9)$$

where

$$T_{NH} = \text{"high" noise diode, K}$$

$$T_{NL} = \text{"low" noise diode, K}$$

Using Eq. (6), the resolution of T_{NL} (step 3 alone), assuming $T_{OP} = 20$ K, $\tau = 10$ s, $B = 10^7$ Hz, $T_N = 1$ K is 0.004 K.

Now, using $T_{OP}|_{AMB} = 300$ K, $T_{OP}|_{ANT} = 20$ K, $T_{NH} = 100$ K, $T_{NL} = 1$ K, $B = 10^7$ Hz and going through the calibration steps above, the calibration resolution, using Eqs. (2) and (6), is

$$(1) \Delta T_{NH} = 0.025 \text{ K} \quad (\tau = 100 \text{ s})$$

$$(2) \Delta T_{OP|ANT} = \sqrt{(0.005)^{2*} + (0.005)^{2**}} \quad (\tau = 10 \text{ s}) \\ \approx 0.007 \text{ K}$$

and

$$(3) \Delta T_{NL} = \sqrt{(0.007)^2 + (0.004)^2} \approx 0.01 \text{ K} \quad (\tau = 10 \text{ s})$$

This analysis neglects all bias errors and antenna/receiver system instabilities and interference. However, the analysis does indicate the basic calibration resolution limit. A 1% resolution (0.01 K) can also be obtained with the low noise diode for this example by calibrating on the ambient termination directly and integrating for approximately 6 minutes.

*If $T_{OP}|_{AMB} = 300$ K and $T_M = 3$ K, a 10% error in T_M results in only = 0.1% error in $T_{OP}|_{AMB}$ (Refs. 3, 4).

*From Step 2, $\Delta T_{OP}|_{ANT} = (\Delta T_{NH})/(Y - 1) = 0.025/5 = 0.005$ K.

**From Eq. (2).

The primary "accuracy" concerns for the NAR are measurement resolution, repeatability as discussed above, bias errors, and "short" and "long" term measurement accuracy deterioration. Measurement resolution is obtained by selecting the system operating parameters (primarily measurement time) to satisfy Eq. (2). The primary concerns regarding bias errors and accuracy deterioration are receiving system linearity and noise diode calibrations.

System non-linearity effects are analyzed in Appendix B and, for example (1), $[T_{ND}(M)|_{AMB} - T_{ND}(M)|_{ANT} \approx 0.1 \text{ K}]$, results in $\Delta T_{OP}|_{ANT} \approx 0.1$. If the actual receiver non-linearity is unacceptable, lower the maser gain (results in higher T_E), upgrade the receiver, use algorithm equation B-3 to reduce the effect or combine techniques to obtain acceptable performance.

III. NAR Performance

The expected noise temperature measurement accuracies (1σ) on the antenna for the NAR (assuming $T_{OP}|_{ANT} \approx 20 \text{ K}$, $T_{OP}|_{AMB} \approx 300 \text{ K}$, $B = 10^7 \text{ Hz}$ and $\tau = 10 \text{ s}$) are summarized in Table 1 for 1 and 100 K noise diodes. It is assumed that the noise diode waveguide coupler has satisfactory directivity. This can be verified by $T_{ND}(M)|_{AMB} = T_{ND}(M)|_{ANT}$ with reduced maser gain.

The function of the NAR is to measure the receiving system operating noise temperature to a specified resolution and accuracy at a prescribed data rate. A manual Y factor method is available in the DSN for comparison noise temperature measurements with the NAR. The manual method consists of switching the receiving input between the antenna and an ambient termination and using a manually operated precision

IF waveguide beyond cutoff attenuator to measure the Y factor. The 1σ accuracy of the manual method is about 2 percent (Ref. 3).

Comparison of the NAR with the manual Y factor method should be performed on a *routine* basis to detect NAR degradation. In addition, the NAR performance is verified by *routine* testing of the critical component elements of the NAR system. These are:

- (1) Measurement resolution (evaluate the noise temperature measurement scatter).
- (2) Linearity verification (using an auxiliary noise diode on the antenna and ambient termination, Appendix B).
- (3) Noise diode calibration (long-term noise temperature calibration monitoring).

The analysis summarized in Table 1 indicates that the NAR has about 1.5 percent (1σ) accuracy potential with the 1 K noise diode (assuming no pathological problems such as RF interference). This level of measurement accuracy requires monitoring of the critical measurement elements indicated above. This analysis assumes satisfactory performance of these critical NAR elements. Unsatisfactory performance (i.e., unstable noise diode waveguide coupler or transmission line connectors, receiver nonlinearity, or RFI) would require appropriate system upgrading.

Indication of unsatisfactory performance should be investigated by monitoring the noise diode calibration over a 24-hr period and correlating with ambient temperature. In addition, the system should be stressed by moving and braking the antenna, manual cable movement, etc.

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Table 1. Summary of NAR measurement errors of system noise temperature on the antenna

	Case	
	1	2
Error source	$T_N = 1 \text{ K}$	$T_N = 100 \text{ K}$
Resolution, Eq. (2)	0.08	0.005
ΔT_N (Resolution, Eq. (6))	0.20 ^a	0.016 ^b
ΔT_N (bias error; assume 0.5%)	0.10	0.10
Receiver nonlinearity, Eq. (B-9) using 10 K auxiliary noise diode	0.10	0.10
$\Sigma \text{error} $	0.05 (2.5%)	0.22 (1.1%)
$\sqrt{\Sigma \text{error} ^2}$	0.26 (1.3%)	0.14 (0.7%)

^a Assumes $\Delta T_N = 0.01 \text{ K}$.

^b Assumes $\Delta T_N = 0.08 \text{ K}$.

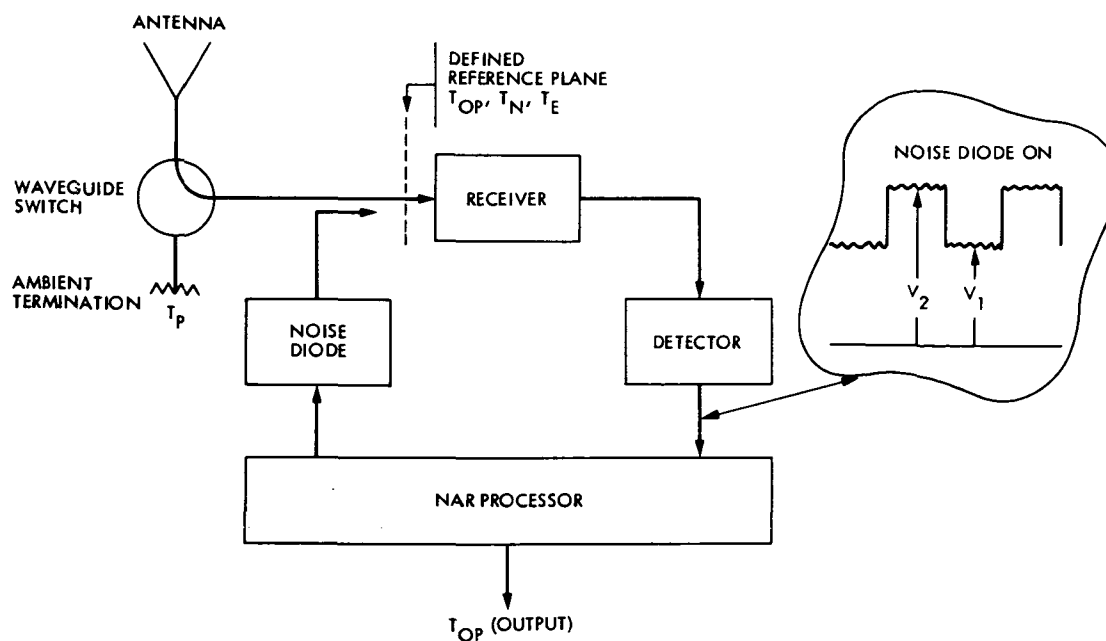


Fig. 1. Microwave receiving system showing NAR configuration

Appendix A

Noise Diode Calibration Resolution

The NAR noise diode can be calibrated (assuming T_{OP} is known) using*

$$T_N = T_{OP} [(V_2/V_1) - 1] \quad (A-1)$$

where

$$V_1 = GT_{OP}, V$$

$$V_2 = G(T_{OP} + T_N), V$$

G = system gain

Use

$$\sigma_{T_N}^2 = \left(\frac{\partial T_N}{\partial V_1} \right)^2 \sigma_{V_1}^2 + \left(\frac{\partial T_N}{\partial V_2} \right)^2 \sigma_{V_2}^2 \quad (A-2)$$

*For calculation of resolution, α in Eq. (1) can be approximated as 0.

$$= T_N^2 \left(1 + \frac{T_{OP}}{T_N} \right)^2 \left[\left(\frac{\sigma_{V_1}}{V_1} \right)^2 + \left(\frac{\sigma_{V_2}}{V_2} \right)^2 \right] \quad (A-3)$$

From total power radiometry theory,

$$\left(\frac{\sigma_{V_1}}{V_1} \right)^2 = \left(\frac{\sigma_{V_2}}{V_2} \right)^2 = \frac{1}{(\tau/2)B} \quad (A-4)$$

where

B = bandwidth, Hz

τ = total measurement time, s (measuring V_1 or V_2 only 1/2 the time)

Then

$$\Delta T_N = 2T_N (1 + T_{OP}/T_N) / \sqrt{\tau B} \quad (A-5)$$

Appendix B

Receiving System Linearity Verification

The NAR system can be used with an auxiliary noise diode to determine the receiving system nonlinearity. This is done by turning an auxiliary noise diode on and off with the receiving system connected alternately to the antenna and then to the ambient termination. The degree of system nonlinearity is indicated by the difference between the increase in system noise temperature with the different input noise power levels represented by the antenna and the ambient termination.

The auxiliary noise diode increases the system noise temperature by (receiving system input connected to the antenna or ambient termination, respectively)

$$T_{ND}|_{ANT} = \tilde{T}_{OP}|_{ANT} - T_{OP}|_{ANT} \quad (B-1)$$

$$T_{ND}|_{AMB} = \tilde{T}_{OP}|_{AMB} - T_{OP}|_{AMB} \quad (B-2)$$

where

T_{OP} = system operating noise temperature (auxiliary noise diode off), K

\tilde{T}_{OP} = system operating noise temperature (auxiliary noise diode on), K

Assume that the corrected and measured system noise temperatures (Ref. 5) are related by (all measured temperatures are identified by M)

$$T_{OP} = \gamma T_{OP}(M) - \beta T_{OP}^2(M) \quad (B-3)$$

where

$T_{OP}(M)$ = measured system noise temperature, K

T_{OP} = corrected system noise temperature, K

β = system non-linearity factor, V^{-1} (= 0 in ideal system)

γ = system nonlinearity factor, ratio (= 1 in ideal system)

Since

$$T_{ND}|_{ANT} = T_{ND}|_{AMB} \quad (B-4)$$

we have

$$\tilde{T}_{OP}|_{ANT} - T_{OP}|_{ANT} = \tilde{T}_{OP}|_{AMB} - T_{OP}|_{AMB} \quad (B-5)$$

From the NAR calibration technique, Eqs. (3) and (4),

$$T_{OP}(M)|_{AMB} = T_{OP}|_{AMB} \quad (B-6)$$

and with Eq. B-3

$$\gamma = 1 + \beta T_{OP}|_{AMB} \quad (B-7)$$

Substituting Eq. (B-3) into (B-5) and solving using Eq. (B-7)

$$\beta = \frac{T_{ND}(M)|_{AMB} - T_{ND}(M)|_{ANT}}{\tilde{T}_{OP}(M)|_{AMB} T_{ND}(M)|_{AMB} + T_{OP}|_{AMB} T_{ND}(M)|_{ANT} + T_{OP}^2(M)|_{ANT} - \tilde{T}_{OP}^2(M)|_{ANT}} \quad (B-8)$$

The error in T_{OP} due to the system nonlinearity is (using $\Delta T_{OP} = T_{OP} - T_{OP}(M)$, with Eqs. B-3 and B-7),

$$\Delta T_{OP} = \beta T_{OP}(M) [T_{OP}(M)|_{AMB} - T_{OP}(M)] \quad (B-9)$$

For example (1),

$$\begin{aligned} T_{OP}(M)|_{ANT} &= 20 \text{ K}, T_{OP}|_{AMB} = 300 \text{ K}, T_{ND}(M)|_{ANT} \\ &= 10 \text{ K}, T_{ND}(M)|_{AMB} = 10.1 \text{ K}. \end{aligned}$$

This results in

$$\begin{aligned} \beta &= \frac{0.10}{(310.1)(10.1) + 300(10) + (20)^2 - (30)^2} \\ &= 1.776 \times 10^{-5} \\ \gamma &= 1 + (1.776 \times 10^{-5}) 300 = 1.0053 \end{aligned}$$

$$\Delta T_{OP}|_{ANT} = 1.776 \times 10^{-5} (20) (300-20) = 0.1 \text{ K}$$

This example is typical of a highly linear receiving system.

Equation (B-3) can be used as in the example for error estimates or alternately as a method to reduce the effects of the receiving system nonlinearity. In the latter case, β and γ are determined from calibrations using the auxiliary noise diode and a corrected T_{OP} is computed from Eq. (B-3). In this

case the linearity error is greatly reduced. This can be verified in practice with the same auxiliary noise diode.

For example (2)

$$\begin{aligned} T_{OP}(M)|_{ANT} &= 20 \text{ K}, T_{OP}|_{AMB} = 300 \text{ K}, T_{ND}(M)|_{ANT} \\ &= 10 \text{ K}, T_{ND}(M)|_{AMB} = 12 \text{ K}. \end{aligned}$$

This results in $\beta \approx 3.203 \times 10^{-4}$, $\gamma = 1.096$ and $\Delta T_{OP}|_{ANT} \approx 1.8 \text{ K}$. Equation (B-3) is shown plotted in Fig. B-1 for this example, chosen to illustrate a highly nonlinear receiving system.

Poor directivity of the waveguide coupler used to inject the noise diode, T_N , could result in $T_{ND}|_{ANT} \neq T_{ND}|_{AMB}$. This is due to the difference in coupling factor of the waveguide coupler when connected to the antenna and ambient load, which in general will not have identical VSWRs. Therefore, if $T_{ND}|_{ANT} \neq T_{ND}(M)|_{AMB}$ it will be necessary to distinguish between poor waveguide coupler directivity and receiver nonlinearity. This can be done using an independent method from the above derivation for receiver linearity verification: (1) calibrate system noise temperatures with normal system gain; (2) recalibrate system noise temperature, with reduced (approximately 10 dB) maser gain accounting for increased maser followup noise temperature (Eq. 5). No change in the calibrations would indicate a linear system.

If low system noise temperature is not critical in a particular application, then maser gain reduction could be a simple operational solution to receiver system nonlinearity.

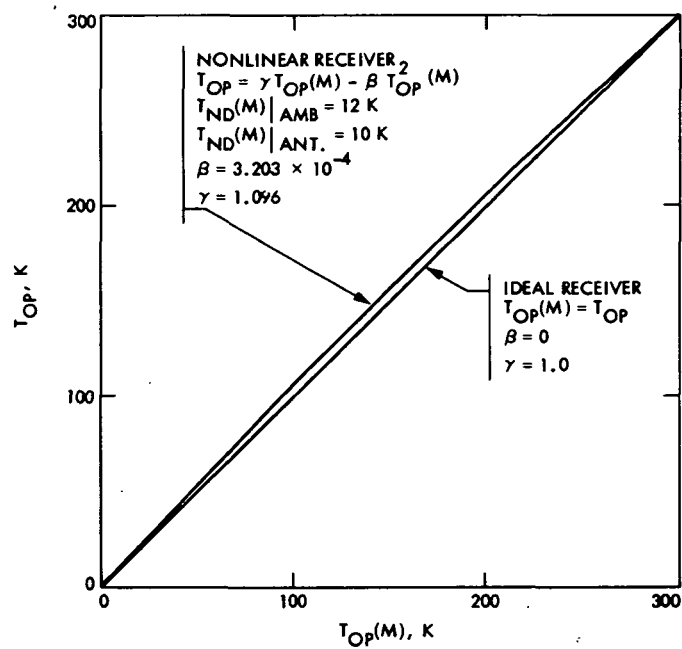


Fig. B-1. T_{op} vs $T_{op}(M)$ for a highly nonlinear receiving system

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